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Magnetic energy analysis of high energy particles

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With 5 figures in the text

ABSTRACT

The experimental arrangement for measurements of 185–120 MeV protons with a magnetic spectrometer is described.

Introduction

High resolution measurements of energy spectra of protons and other charged particles have been made with range telescopes [1] with total energy analysing crystals [2] and with the magnetic analyser of this Institute. An important advantage of a magnetic analyser over the other two devices is that the tail at the low energy side of a peak in the spectrum is several orders of magnitude lower. For this reason it has until now been possible only with a magnetic analyser to measure spectra in which the elastic peak is a hundred or a thousand times more intense than a typical inelastic one. This is the case at very small scattering angles. For high energies the angular distributions are compressed in the forward direction and the most interesting features occur just at small scattering angles, roughly between 0 and 15 degrees. Therefore this advantage of a magnetic analyser may well outweigh its disadvantages, the most important one being its large size and the fact that it is rather expensive and time-consuming to build.

It is the purpose of this paper to describe the experimental arrangement used for measurements with the magnetic analyser of this Institute.

The analyser magnet and auxiliary equipment

The analyser magnet uses a 90° sector-shaped uniform field which gives two-directional focusing. The theory and general features of the instrument have been reviewed in ref. [3]. The important parameters of the instrument as used in the arrangement to be described are summarized below.

Radius of curvature	94 cm	Width of tapered pole gap	7.5 cm
Distance from source to magnet entrance	94 cm	Deflecting angle	90°
Distance from magnet exit to image	82 cm	Height of entrance slit	0.6 cm
Height of pole gap	1.6 cm	Width of entrance slit	1.5 cm
		Width of defining crystal	0.35 cm

A section of the magnet and auxiliary equipment is shown in Fig. 1.

Each the two coils of the magnet consists of 990 windings of 50 × 0.5 mm water cooled copper band.

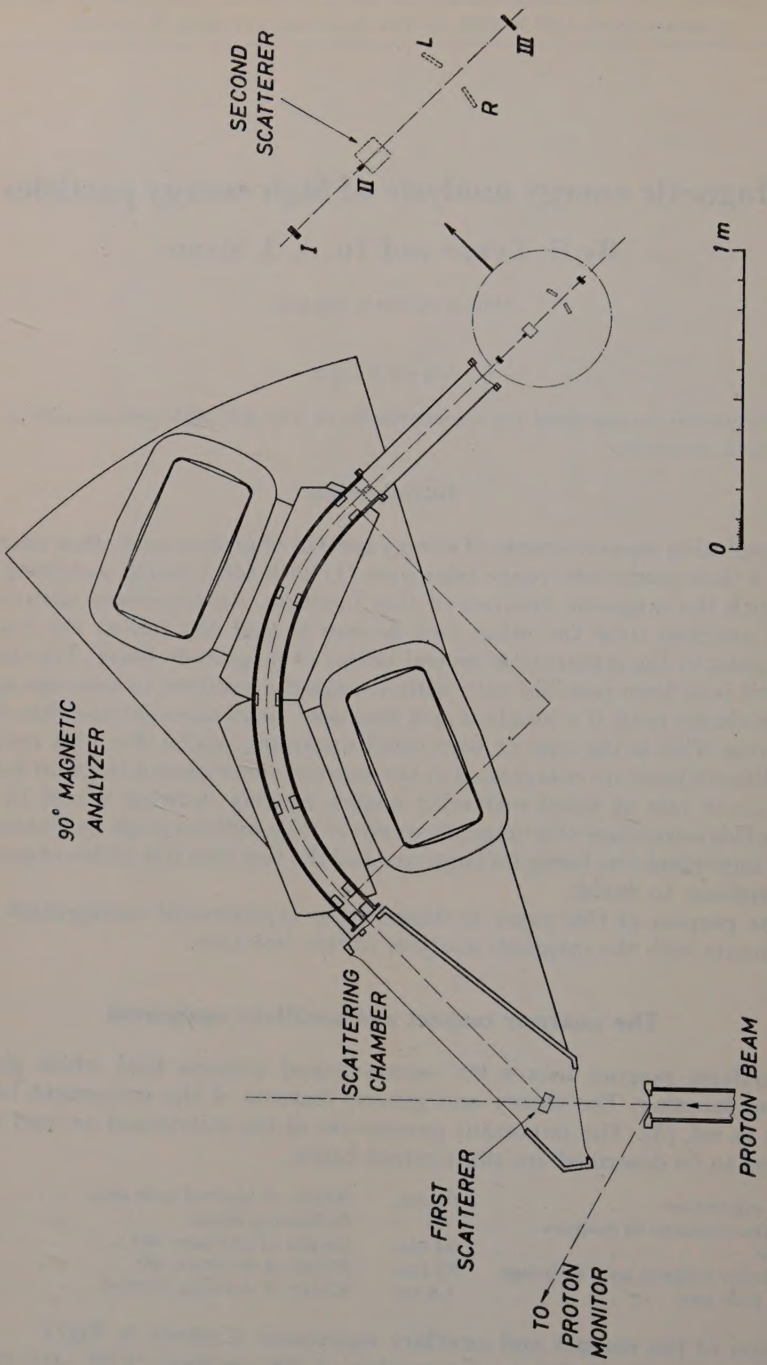

Fig. 1. Schematic diagram of the apparatus.

The current in the magnet is produced by a 20 kilowatt, 230 V motor generator which delivers a maximum current of 87 amperes.

The current is stabilized by means of two regulators (one being the fine regulator), each of which acts on one field coil of the D.C. generator. The current in the magnet coils passes through a resistor, and the voltage drop over this resistor, 300 mV at 100 amperes, is compensated by a highly stabilized variable reference voltage. The difference voltage feeds the amplifier of the regulator which acts on the field coils of the generator and determines the current in the magnet.

The current stability over long periods has been measured and is for 30 amperes 0.015 % and at 5 amperes 0.08 %. The magnet field stability is even better because of saturation of the iron.

The magnet field has been accurately measured for different currents in the coils at some central points of the magnet gap by using the proton resonance method. Differences in the field in the median plane along the central path and perpendicular to this path have been measured using two counter current coils connected to a toroid galvanometer. The field is nearly homogeneous in the region used for the particle orbits.

The target is mounted in an evacuated chamber in the scattering center. Thin mylar windows are used where the proton beam enters and leaves the chamber and at the exit of the scattered protons. Care is taken in the design of the scattering chamber to minimize distortions in the inelastic spectra due to elastically scattered particles from the mylar windows.

The pole tips of the magnet make part of another evacuated chamber. This also has thin mylar windows at the ends.

The scattering chamber, the magnet and the detectors are mounted on a rigid support which can be moved on rails around the scattering centre and set at the desired angle by a remotely controlled motor and position indicator. The target is automatically positioned perpendicular to the proton beam or perpendicular to the direction of the scattered protons or in the bisector of these directions.

The proton beam is monitored by a double coincidence telescope looking at the aluminium end window of the proton tube. The detector counters are automatically switched off after a preset number of monitor counts.

The protons which have passed through the magnet are counted by a telescope of three plastic scintillators I, II and III in coincidence, II being the defining crystal. Crystal I and III are sufficient wide to cover the angular spread of protons emerging from the magnet. An absorber is put in front of crystal III to stop protons having energies below ≈ 100 MeV.

As described in some detail in ref. [4] the polarization of protons passing through the energy defining crystal can be determined by using a second scatterer and measure the left and right hand scattering in this second target by means of two side counters L and R. In this case coincidences between I, II and L, and I, II and R are counted. Counter III is used in anticoincidence to reduce accidental coincidences caused by coincidence counts in I and II due to the bulk of protons which pass through these counters and counter III, combined with accidental counts in L or R.

The photomultipliers used are EMI 6097B. The pulses from the last dynodes are fed through a cathode follower into a simple pulse shaping circuit. In this circuit the pulses are amplified and divided into two outputs. The output pulses are ≈ 4 V negative, and have a length of approximately twice the risetime of the photomultiplier.

In the polarization experiments two triple coincidence plus anticoincidence mixers are used. Accidentals are in this case measured by connecting a 40 mμsec. delay cable, the delay time being equal to the high frequency period of the synchrocyclotron. The delay is switched on and off by a remotely controlled relay.

The mixers are somewhat modified Rossi type circuits. In these mixers the coincidence pulses are clipped to 8 mμsec length which is thus the time resolution of the system. As a check the two mixers may be used as triple coincidence mixers in running the inelastic spectra. They should then both give equal number of counts.

Requirements on the beam

Up to now the magnet has been used for measurements on scattered protons. In order to get a good energy resolution and reproducibility the requirements to be put on the quality of the beam are high.

The initial energy spread of the beam limits the obtainable resolution and should therefore be small.

A monoenergetic group of scattered protons may be focused by the analyser magnet in an image. The width of this image in the horizontal plane, together with the width of the defining detector, determine the width of the peak in the spectrum corresponding to the proton energy. The size of the image is again proportional to the portion of the target from which the protons emerge, as seen from the magnet entrance. Therefore another condition on the beam is that it should be narrow in the horizontal direction.

The magnet gap has a flat geometry and therefore the transmission is very dependent on the height of the irradiated part of the target. To use the beam intensity effectively, the beam should be narrow in the vertical direction.

Movements of the beam in the horizontal direction simulate energy variations in the measurements and movements in the vertical direction decrease the transmission, causing dips in the spectrum. For these reasons variations of the beam position in both directions should not exceed a few tenths of a millimeter.

Summarizing, the beam is required to have a small energy spread, to be narrow, and to be stable in position.

The beam of the Uppsala synchrocyclotron has an energy spectrum with a full width at half height of 1 MeV or less. It may be focused on the target in a spot about 4 mm in diameter (see Fig. 2). Its geometrical stability during a run is in general good, but occasionally a jump into a new position which may differ from the previous one by one or two millimeters occurs. The reason is probably a short circuit in the cyclotron magnet coils. The position has therefore to be checked several times during a long run. This is done by taking a photograph of the beam at the target centre or by measuring the height of a known peak. The beam position can be corrected by adjusting the quadrupole magnets which focus the beam. Recently a pair of horizontal and vertical deflecting magnets have been built which can be used to adjust the beam.

The trimming of the magnet

The magnet can be used with different gap widths, the choice of which is dependent on the magnetic rigidity of the particles under study. For 120–180 MeV protons a gap of 16 mm is used.

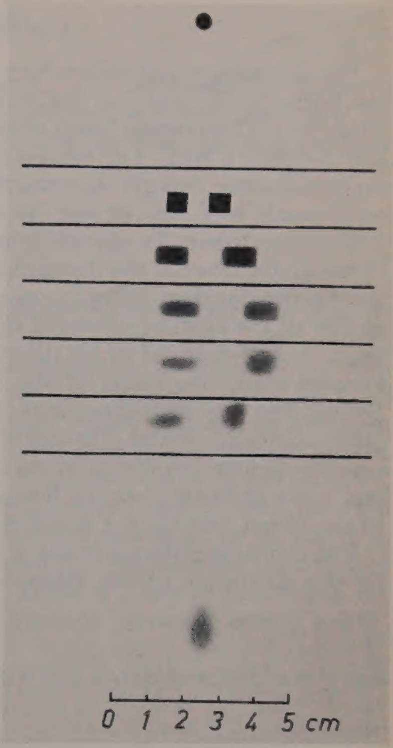

Fig. 2. Photograph of the beam at the position of the target, at the position of the five central slits and in the image plane when two entrance slits of 5 × 5 mm are used.

In order to study the paths of the particles between the target and the detectors a frame with photographic films in 5 different positions was put into the magnet gap. The magnet was set at 0 degrees, in the direct cyclotron beam. The photographs showed that some extra windings on the second yoke (looking in the beam direction) were needed to make the particle orbits follow the central path. Furthermore it turned out that stray particles made the image diffuse and therefore a series of thick copper slits was introduced (see Fig. 1). By varying the slit positions and widths a satisfactory image was finally achieved. Fig. 2 shows pictures taken at the position of the five slits when two 5 × 5 mm slits, spaced 5 mm apart, were used as entrance slits of the magnet. This fig. also shows a picture of the beam in the focusing plane which was found to be 82 cm from the exit of the magnet. However, for unknown reasons the focusing properties of the magnet become worse at energies of 120 MeV and lower, a fact which manifests itself in a rather sudden drop of the transmission at these energies. As our interest in the inelastic proton spectra has been mainly in the energy region over 130 MeV, we have not yet further investigated this behaviour. In the final situation the entrance slit was 6 × 15 mm.

Calibration

Absolute figures for energies and cross sections can be obtained by calibrating the magnet with protons scattered in processes for which the energy losses or cross sections are known.

(a) Energy calibration

For the energy calibration free proton-proton collisions in polythene, the elastic scattering in Be, and the scattering from the 4.43 MeV and 9.61 MeV states in C^{12} were used. The average beam energy has been measured with an absorption method and is 185 ± 1 MeV. The *relative* energies are very insensitive to small errors in the mean incoming energy. As remarked earlier, the actual spread in the beam energy corresponds to 1 MeV or less full width at half height.

The target (usually about 1 g per cm^2 thick) is put perpendicular to the bisector of the angle between the incoming beam and the relevant scattering direction. From the known incident energy, correcting for the energy absorbtion in the target, the energy of the protons scattered in a certain direction can be calculated. A measurement of the current at which the maximum of the corresponding peak in the spectrum appears gives one point of the energy versus magnet current calibration curve. By varying the scattering angle the energy of the scattered protons changes and other points are found. The calibration curve so obtained was checked and in some regions slightly improved by measuring the energy differences between the elastic and some inelastic peaks in Be and C, of course correcting for the energy absorption in the target and for the recoil energy of the nucleus.

The resulting calibration curve is shown in Fig. 3. Its shape is evidently influenced by the saturation of the magnet yokes.

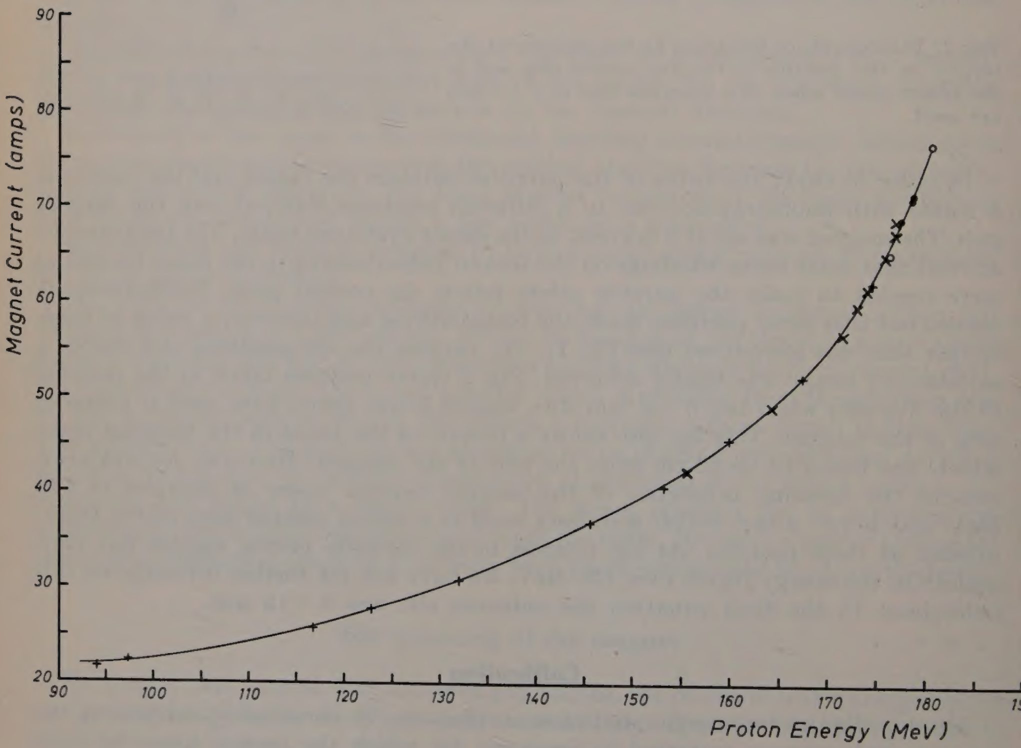

Fig. 3. The calibration curve of the magnet.

(b) Transmission calibration

Clearly the area of a peak in a spectrum caused by a monoenergetic group of scattered particles is proportional to the cross section for the scattering event, the number of target nuclei and the number of bombarding particles. The detectors are assumed to have a constant efficiency.

$$\text{Area of peak} = \frac{1}{\varepsilon} \cdot \frac{d\sigma}{d\Omega} \cdot N \cdot M. \tag{1}$$

The meaning of the symbols is: $d\sigma/d\Omega$ is the differential cross section for the scattering event which causes the peak in the spectrum; N is the target thickness in gram atoms per cm^2; M is the number of monitor counts during the measurement of each point of the spectrum; ε is a proportional factor which is reciprocally proportional to the transmission and depends only on the energy of the particles in question.

For the determination of ε again the free proton peak from scattering in polythene has been used. The number of counts was plotted versus the energy of the scattered protons which was obtained from the corresponding magnet current with the help of the energy calibration curve. The area of the peak was measured. In (1) the area, N and M are now known and $d\sigma/d\Omega$ is the measured p-p cross section, transformed to our energy and to the laboratory system [5]. Therefore ε can be calculated. By varying the scattering angle ε can be determined over the necessary energy region. The energy dependence of ε is shown in Fig. 4.

For a measured spectrum one can transform the count numbers immediately into cross section units by the formula

$$\frac{d^2\sigma}{d\Omega\, dE} = \varepsilon \cdot C \cdot 1/M \cdot 1/N, \tag{2}$$

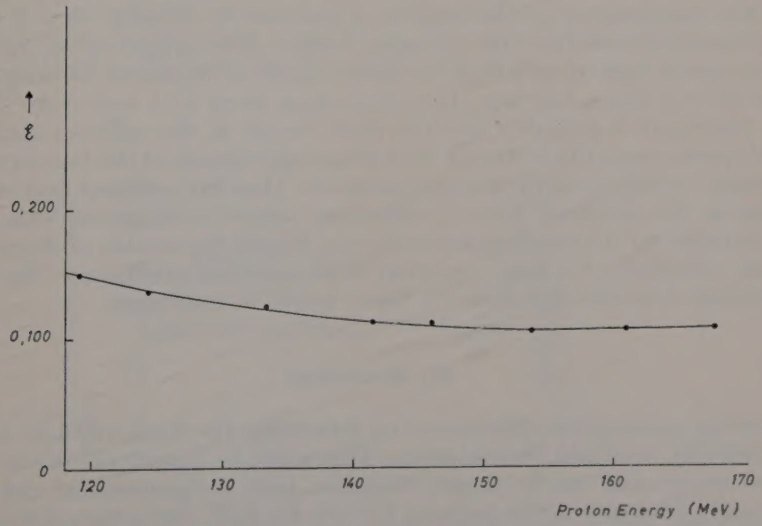

Fig. 4. The proportional factor ε as a function of proton energy.

where C is the number of counts for a certain magnet current during M monitor counts, and N is the target thickness in gram atoms per cm^2. ε is the transmission coefficient corresponding to the appropriate magnet current. The equivalence of (1) and (2) is seen by integrating (2) over the energy region of a peak, neglecting the change of ε over the energy width of the peak.

Of course in using (2) care must be taken that since the calibration nothing has changed in the magnet, detectors, monitor, beam position, etc. This is most simply checked by measuring the height (h_1) of a definite peak from a certain target in the calibration situation and remeasuring its height (h_2) before a run. The measurements have then to be corrected by multiplying the count numbers by the factor h_1/h_2.

Properties

(a) Reproducibility

If one measures a spectrum from one target at a certain scattering angle on two different days, using such high count numbers that the statistical errors are negligible, the two spectra are not exactly congruent. In general they are slightly displaced in energy, say by one or two MeV, and also the absolute count numbers may differ by something like 10 %. The relative numbers of one run reproduce well; this error is generally under 5 %.

The displacements in the energy scale between two runs have turned out to be due to the short circuit in the cyclotron magnet coils mentioned above. It is planned to stabilize the beam energy. However, the effect is not serious for the measurements of the inelastic proton spectra. The measurement of a spectrum takes in general only a few hours and a check before and after the measurement, say of the position of the elastic peak, shows any jump in the energy.

The difference between the numbers of counts at corresponding spectrum energies on different days is also mainly due to changes in the beam, in this case in the beam height. The transmission of the magnet is reduced by roughly 20 % if the beam height differs by 2 mm from the optimum height. Photographs of the beam at the scattering centre have shown that the beam height is in general constant during a period of several hours, but may then jump up or down by 1 mm or so. The reason for this behaviour is probably also the short circuit in the cylotron magnet coils. To avoid errors, every run is started by taking a photograph of the beam and correcting its height by adjusting the focusing magnets. Then the counting rate of a certain maximum in the spectrum from a calibration target is measured. This gives the correction factor for the transmission in the run. During the run the calibration peak is repeatedly measured; if a large variation in its counting rate occurs, the uncertain measurements are cancelled, and the beam height is readjusted.

(b) Resolution

The energy resolution is determined by measuring the total width at half height of an elastically scattered proton group. This width is dependent on the spread in the beam energy and on the target thickness, both for geometrical and energetic reasons, and varies in practice between 1.6 and 2.0 MeV. For a very thin target and a monoenergetic beam the finite resolution is caused by the following two factors.

Firstly, the horizontal width of the image which the magnet makes of the spot where the beam hits the target. This width will be dependent on the horizontal dimensions of the beam and on the magneto-optical properties of the magnet.

Secondly by the width of the defining detector in the focus of the magnet. The crystal should be considerably narrower than the size of the image.

(c) Small angle measurements

A peak in a measured spectrum has a tail extending through the whole spectrum from the peak energy downwards. For the analyser magnet at an energy a few MeV lower than the peak energy the height of the tail is already of the order of one thousandth of the peak height. The tail is caused by particles scattered on the slits in the magnet, by straggling in the target and perhaps also by a tail in the energy spectrum of the beam. At very small angles the elastic peak is very high and then the tail of this peak can become of the same order of magnitude as the inelastic part of the spectrum. This causes not only a continuous background which is difficult to subtract, but also, ultimately, a structure which may simulate a non-existent structure in the spectrum. A correction for this effect is difficult, because the tail is dependent on many factors and does not reproduce for different runs and targets. Therefore the height of the elastic peak puts a lower limit on the usable scattering angles. In light elements like carbon measurements down to 3.2 degrees have been possible, but the spectra of the heavy elements become unreliable already at 10 degrees. As a rough rule one may say that the spectrum starts to be badly deformed in the neighbourhood of the elastic peak if this peak is 1000 times higher than the average height of the inelastic contributions. This hehaviour may be observed in the spectrum of Fig. 3 of ref. [6].

(d) Errors

From the foregoing discussion it is easy to estimate the errors in a typical measurement. The irreproducibility causes an error of roughly 5 % if some care is taken during the measurements. To this must be added the statistical errors and the uncertainty of the transmission coefficient, which is mainly caused by the error in the p-p cross section used.

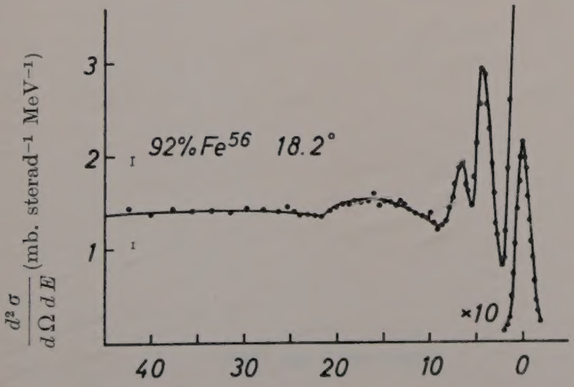

Fig. 5. Energy spectrum of 92 % Fe^{56} at 18.2°. The horizontal scale shows the excitation energy of the residual nucleus in MeV.

The energy determination has been checked with known levels and the error did not exceed 2 % of the excitation energy.

Fig. 5 shows a typical spectrum obtained as an illustration of the quality of the spectrometer.

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